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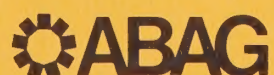
EARTHQUAKE INTENSITY AND EXPECTED COST

in the San Francisco Bay Area

February 1978

Earthquake Preparedness Program

ASSOCIATION OF BAY AREA GOVERNMENTS



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E R R A T A

The Concord-Green Valley fault and Antioch fault labels on Plates 2a & b and 3a & b are in the wrong location. The map itself is correct, however. The location labeled Antioch fault is actually the Concord-Green Valley fault and the Antioch fault is actually farther east. (The darker areas on Plate 1 can help you identify the correct locations.) Please note this change while reading this report.



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EARTHQUAKE INTENSITY AND RELATED COSTS IN THE SAN FRANCISCO BAY AREA

February 1978

Association of Bay Area Governments

EARTHQUAKE INTENSITY AND RELATED COSTS IN THE SAN FRANCISCO BAY AREA

Two Types of Earthquake Maps and Their Uses

Earthquake intensity and cumulative economic risk maps for earthquake damage may well become valuable planning tools in the Bay Area.

An earthquake intensity map groups together a variety of different causes of earthquake damage; although shaking is the dominant cause of damage, other factors such as liquefaction, landsliding, fault rupture, and changes in ground level can also contribute to intensity. Plate 1 is an example of a maximum earthquake intensity map for the San Francisco Bay Area. This map is not the only maximum intensity map that can be developed; altering the way that intensity is related to distance from a fault can produce a different map. The intensities shown on the map can be converted to damage for two types of buildings using Table 8. This type of map can be used with information on existing buildings to forecast locations of maximum damage for use in planning emergency response measures and for designating areas of critical concern.

A cumulative economic risk map can relate the expected damage to particular types of buildings over time. Such maps rely on intensity information as well as information on the amount of damage that can be expected for each intensity and general type of building and information on how often a particular earthquake is likely to occur. Plates 2a & b, and 3a & b, are examples of risk maps. They indicate the total expected percent damage due to earthquakes resulting from any of the major active faults in the Bay Area for any given area for two types of small buildings: wood-frame (Plates 2a and 3a) and other types (Plates 2b and 3b). Risk maps may be used in evaluating the relative costs due to earthquakes for new buildings in various locations throughout the region and for designating areas where special precautions may be needed. However, the intensity-cost information is not a sufficient basis for engineering decisions at a specific site, for these require specific knowledge of the process causing damage. Note that the graphic appearance of a risk map is very dependent on how often earthquakes are assumed to occur on each fault. Plates 2a and b use a different set of recurrence intervals than Plates 3a and b.

This report documents the way in which both intensity maps and risk maps can be produced. The information used and assumptions made in developing the maps on Plates 1-3 are also discussed. The sample map of "Maximum Expected Earthquake Intensity" (Plate 1) is described first since it is the simplest.

MAPPING MAXIMUM EXPECTED EARTHQUAKE INTENSITY

A large earthquake on any one of several faults in the Bay Area could cause damage. The maximum intensity in a specific area due to any earthquake originating on any fault depends on the exact ground motion characteristics of the earthquake, the distance of the area from the fault that slips, and the type of geologic material that underlies the area. The intensity can be related to predicted damage by taking into account the general type of construction of the buildings in the area.

Three U.S. Geological Survey scientists, Borchardt, Gibbs and Lajoie (1975) have developed a procedure for estimating the maximum intensity. The maximum earthquake intensity map shown on Plate 1 uses their method with a couple of minor changes. The steps in producing this map are as follows:

1. Divide the geologic materials into six categories with similar ground shaking amplification characteristics.
2. Eliminate those materials of insignificant depth to influence the ground shaking characteristics.
3. Choose those faults to be considered active.
4. Estimate the maximum magnitude earthquake which can be associated with each active fault.
5. Relate the materials and expected intensities to distances from faults using formulas developed by Borchardt, Gibbs and Lajoie (1975).
6. Adjust the maximum intensity rating using the estimate of maximum magnitude.
7. Produce maximum intensity maps for each fault using the maps of faults and materials and the tables of distances and intensities.
8. Combine the maps for individual faults into a single fault map by using the largest intensity that occurs in any given area.

Each of these steps is described below in detail.

STEP 1: CATEGORIZING GEOLOGIC MATERIALS

The basic geologic information has been derived from U.S. Geologic Survey and California Division of Mines and Geology Maps at scales of 1:62,500 and 1:125,000. This information is the most appropriate uniform coverage available for the entire region. A list of the maps

used is given in Table 1, below. Data from the maps were generalized into six categories of materials with similar ground shaking amplification characteristics according to Borchardt, et al. (1975). The six categories are:

1. Granitic Rocks
2. Franciscan Assemblage
3. Most Tertiary and Older Rocks
4. Quaternary-Tertiary Rocks
5. Alluvium
6. Bay Mud

Other categories of geologic materials have been suggested.

TABLE 1: SOURCE MAPS FOR GEOLOGIC MATERIALS

<u>AREA</u>	<u>COMPILED BY</u>	<u>AGENCY</u>	<u>SCALE</u>
Western Sonoma Co and Northernmost Marin County	Blake, Smith, Wentworth, and Wright	USGS	1:62,500
Marin and S.F. Cos., part of Alameda, Contra Costa, and Sonoma Cos.	Blake, Bartow, Frizell, Schlocker, Sorg, Wentworth, and Wright	USGS	1:62,500
Southern Bay Region	Borchardt, Gibbs, and Lajoie	USGS	1:125,000
Contra Costa Co.	Brabb	unpublished	1:62,500
Santa Clara Co.	Brabb and Dibblee with Rogers and Williams	CDMG from USGS data	1:62,500
San Mateo Co.	Brabb and Pampeyan	USGS	1:62,500
Eastern Sonoma Co., and Western Napa Co	Fox, Sims, Bartow, and Helley	USGS	1:62,500
Solano Co., and parts of Napa, Contra Costa, Marin and Yolo Cos.	Sims, Fox, Bartow, and Helley	USGS	1:62,500

STEP 2: GENERALIZING GEOLOGIC MAPPING

Some materials are too thin to affect the ground shaking characteristics. Although small or narrow deposits are not necessarily thin, those materials with an areal extent of less than 1/2 km were eliminated in an attempt to deal with the problem of accounting for thin materials. The areas were eliminated by using a quarter square kilometer grid cell (i.e., 1/2 km on each side). Not enough three dimensional geologic control is available to eliminate thin materials more rigorously.

STEP 3: CHOOSING THE ACTIVE FAULTS

The major active faults to be examined were selected after several sources of active faults were considered. The two most reliable lists are those compiled by the State Geologist to implement the Alquist-Priolo Special Studies Zones Act and by the U.S. Geological Survey in Bulletin 941-A (Borcherdt, 1975) listing faults that are known to have produced small earthquakes or are capable of producing an earthquake of at least a magnitude 4*. The two lists are shown below in Table 2. As one would expect there is a great deal of similarity between the two lists. However, the Tolay and Alexander Valley faults are only listed by the California State Geologist and the Sargent, Berrocal, Zayante, and Black Mountain faults are only listed by the Survey. The decision was made to use only those faults appearing on both lists. The Tolay and Alexander faults are therefore omitted since they have had no recorded earthquakes in historic time; the Sargent, Berrocal, Zayante, and Black Mountain faults have been omitted because they are not zoned by the State Geologist.

TABLE 2: MAJOR ACTIVE FAULTS

<u>AS COMPILED BY THE STATE GEOLOGIST</u>	<u>AS COMPILED BY THE U.S. GEOLOGICAL SURVEY</u>
San Andreas	San Andreas
San Gregorio	San Gregorio
Hayward	Hayward
Healdsburg-Rodgers Creek	Healdsburg-Rodgers Creek
NE of Alexander	NE of Alexander
Pleasanton	Pleasanton
Calaveras	Calaveras
Concord-Green Valley	Concord-Green Valley
---	Sargent
---	Berrocal
Antioch	Antioch
Silver Creek	Silver Creek
---	Zayante
---	Black Mountain
Tolay	---
Alexander Valley	---

Most faults were mapped using the CDMG 1:24,000 maps prepared for implementing the Alquist-Priolo Act. Those fault segments under water were extrapolated from CDMG maps when possible. The underwater segment of the northern San Andreas between the Bolinas and South San Francisco quadrangles was mapped using USGS 1:62,500 maps.

* The smallest magnitude thought to cause damage under typical Bay Area building standards.

STEP 4: ESTIMATING MAXIMUM MAGNITUDE

The maximum probable earthquake can be related to the length of the fault trace. The magnitudes for each fault, or fault segment, are given in Table 3, below. Except as otherwise noted, the magnitudes have been obtained from Borchardt (1975, Table 1 with footnote #8) and rounded to the nearest half magnitude.

TABLE 3: MAXIMUM MAGNITUDE OF MAJOR ACTIVE FAULTS IN THE BAY AREA

<u>FAULT</u>	<u>MAX. MAGNITUDE</u>
San Andreas	8.5*
San Gregorio	8 **
Hayward	7
Healdsburg-Rodgers Creek	7
NE of Alexander	6.5
Pleasanton	4.5
Calaveras	7.5
Concord-Green Valley	6
Antioch	6.5
Silver Creek	6

STEP 5: RELATING MATERIALS AND INTENSITIES TO DISTANCE

After the 1906 earthquake in San Francisco, a study was undertaken to map earthquake intensity throughout the city (Wood, 1908). Since there was no instrumentation, this scale necessarily had to be based on qualitative appraisals of intensity based on damage, amount of surface rupture, and personal accounts. This scale, called the San Francisco scale, has five categories labeled A through E in order of decreasing intensity.

Recently, Borchardt, Gibbs and Lajoie (1975) analyzed the 1906 intensity map and developed a formula to predict the intensity, on the San Francisco scale, for a parcel of land underlain by the Franciscan Assemblage based on the distance of this parcel from the fault that causes the ground shaking assuming an event similar to the 1906 event. This formula is:

$$\text{Predicted San Francisco Intensity} = 2.69 - 1.9 \log (\text{distance in km}) \\ (\text{using 4-0 instead of A-E})$$

Borchardt, Gibbs, and Lajoie also developed a method of adjusting these relations for land that is underlain by other formations using nuclear explosion data. Table 4 shows the intensity increments that must be added to the predicted intensities to correct the formula for each of the geologic materials.

* Source: Wallace (1970)

** Source: Lajoie (1976)

TABLE 4: STATISTICS FOR INTENSITY INCREMENTS
FOR VARIOUS GEOLOGIC MATERIALS CATEGORIES

<u>GEOLOGIC UNIT</u>	INTENSITY INCREMENT (Add to Intensity from Above Equation)	
	<u>(1906 San Francisco Scale)</u>	
	<u>MEAN</u>	<u>STANDARD DEVIATION</u>
Granitic Rocks	-0.29	0.21
Franciscan Assemblage	0.19	0.47
Most Tertiary and Older Rocks	0.64	0.34
Quaternary-Tertiary Rocks	0.82	0.48
Alluvium	1.34	0.58
Bay Mud	2.43	0.58

Using these relations, one can calculate the predicted intensity for a 1906 magnitude event and for a given geologic unit given the distance to the fault trace (Table 5).

Other intensity-distance relationships are being developed.

TABLE 5: MAXIMUM DISTANCE IN KILOMETERS FROM FAULT TO EACH INTENSITY
FOR EACH GEOLOGIC MATERIAL CATEGORY (1906 EVENT)

<u>GEOLOGIC MATERIAL</u>	<u>SAN FRANCISCO INTENSITY</u>				
	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>
Granitic Rocks	0.14	0.48	1.6	5.56	18.
Franciscan Assemblage	0.26	0.86	2.9	9.8	33.
Most Tertiary and Older Rocks	0.44	1.5	5.0	16.	57.
Quaternary-Tertiary Rocks	0.55	1.9	6.2	21.	70.
Alluvium	1.1	3.5	12.	39.	130.
Bay Mud	3.9	13.	44.	150.	500.

STEP 6: ADJUSTING THE MAXIMUM INTENSITY

To estimate the distances from a fault to the intensity boundaries for events smaller than that of 1906, it has been assumed that intensity, for the range of interest, is linearly related to magnitude. This assumption is commonly made in site analysis (see, for example, Cornell, 1968). Thus, if a magnitude 8 can produce a maximum intensity of A at a particular site, then a magnitude 6 can only produce a maximum intensity of C. The maximum intensity assumed for each fault is provided in Table 6. In addition, the pattern of intensities is assumed to be the same,

with the values in Table 5 still being applicable. However, for an earthquake with a maximum intensity of, for example B, the zone closest to the fault, shown as A on Table 6, would become B. The next zone, shown as B, would become C, and so on.

TABLE 6: ESTIMATED MAXIMUM INTENSITY OF MAJOR ACTIVE FAULTS IN THE BAY AREA

<u>FAULT</u>	<u>ESTIMATED MAX. S.F. INTENSITY</u>
San Andreas	A
San Gregorio	A
Hayward	B
Healdsburg-Rodgers Creek	B
NE of Alexander	B
Pleasanton	E
Calaveras	B
Concord-Green Valley	C
Antioch	B
Silver Creek	C

STEP 7: PRODUCING MAXIMUM INTENSITY MAPS FOR EACH FAULT

Maximum intensity maps were produced for each major fault by a VARIAN mini-computer using ABAG's BASIS programs* by overlaying the distance contours of Table 5 as modified by Table 6 with the geologic materials map.

Since each fault was defined by Special Studies Zones delineated by the California Division of Mines and Geology rather than by lines, the fault line was assumed to lie 0.2 km inside the study zone boundary.

STEP 8: PRODUCING A SINGLE MAXIMUM INTENSITY MAP

The intensity maps for individual faults were combined into a single fault map by mapping the largest estimated intensity that occurs in any given area. Thus, if an area could expect an intensity of B from an earthquake on the northern San Andreas, a C from one on the northern Hayward, and an E from one on the Calaveras, the area would be mapped as expecting a maximum intensity of B.

MAPPING TOTAL EXPECTED EARTHQUAKE DAMAGE

At times it is more desirable to have an estimate of the total damage over time that can be expected from any fault affecting the area, rather than the damage from any particular event. Such an estimate requires knowledge of the distribution of frequency of various sized earthquakes on the faults being considered and of the relationship between intensity and damage.

* BASIS is the acronym for ABAG's Bay Area Spatial Information System.

The estimated damage can be mapped using the following procedure:

1. Produce the fault intensity maps described in Step 7 of the previous discussion.
2. Assign magnitude-frequency distributions to each fault.
3. Relate San Francisco intensity to damage for selected building types.
4. Weight the fault intensity maps using the total expected damage.
5. Sum the expected costs due to all faults for each area.

Each of these steps is described below in detail.

STEP 1: PRODUCING MAXIMUM INTENSITY MAPS FOR EACH FAULT

The maps produced in Step 7 of the procedure to produce a maximum intensity map were starting maps in this procedure.

STEP 2: ASSIGNING MAGNITUDE/FREQUENCY DISTRIBUTIONS

The next step in calculating total expected damage due to earthquake ground shaking is to associate each of the major faults with the likelihood of occurrence of events of several different magnitudes. The current model of earthquake generation makes it seem improbable that one would have both a continuing series of moderate events and a large event on the same section of the same fault. Thus, the occurrence of different magnitude events is not independent. This relationship greatly complicates the task of estimating the expected damage. The frequency-magnitude relation has become a standard means of describing the seismicity of a given area. The b-coefficient in this relationship describes the relative proportion of small and large events that occur. An accurate b-value could therefore be used to estimate the distribution of occurrence of events of several different magnitudes. However, time variations and spatial variations in b-values in the Bay Area place such an analysis of distribution beyond the current state-of-the-art (Cramer, 1973). Therefore, for the purposes of this project, it has been assumed that the only earthquake that will occur is the maximum probable earthquake for that fault.

The frequency of the maximum probable earthquake on the San Andreas fault system can be related to the overall rate of strain accumulation in the system. Estimates of strain accumulation may be different for different fault segments.

Because so little is known about recurrence intervals at the present time, two sets of earthquake damage maps using two sets of recurrence intervals have been produced. The two sample sets of recurrence intervals are listed in Table 7, below. The extreme sensitivity of the

maps to recurrence interval can be seen by comparing the shade adjoining the San Gregorio fault in southwestern San Mateo County when a 100 year recurrence interval is assumed (Plates 2a and 2b) and when a 1000 year recurrence interval is assumed (Plates 3a and 3b).

TABLE 7: RECURRENCE INTERVALS FOR MAJOR ACTIVE FAULTS IN THE BAY AREA

<u>FAULT</u>	<u>RECURRENCE INTERVALS</u>	<u>RECURRENCE INTERVALS</u>
	FOR PLATES 2a & b	FOR PLATES 3a & b
San Andreas	100	100
San Gregorio	100	1000
Hayward	100	100
Southern Hayward	100	1000
Healdsburg-Rodgers Creek	100	100
NE of Alexander	100	1000
Pleasanton	100	1000
Calaveras	100	100
Concord-Green Valley	100	100
Antioch	100	100
Silver Creek	100	1000

STEP 3: RELATING INTENSITY TO DAMAGE FOR EVENTS

Estimates of damages to modern wood frame and other types of structures are not available for the San Francisco intensity scale. They are available, however, for the modified Mercalli intensity scale (Page, et al., 1975). These figures are shown in Table 8. Damage resulting from fire is not included directly in these factors. The estimated corresponding San Francisco intensity is also included.

TABLE 8: DAMAGE COST FACTORS* FOR BUILDINGS
ASSOCIATED WITH SELECTED INTENSITIES

<u>MODIFIED MERCALLI INTENSITY</u>	<u>ESTIMATED SAN FRANCISCO INTENSITY</u>	<u>DAMAGE COST FACTOR (%) FOR</u>	
		<u>WOOD FRAME DWELLINGS</u>	<u>OTHER NEW BUILDINGS</u>
VI	E	<0.2 (0.1)	<1 (0.5)
VII	D	2	5
VIII	C	5	15
IX	B	8	35
X	B	12(10)	>50(40)
XI - XII	A	(20)	(75)

* The damage cost factor is equal to the cost of repair divided by the replacement cost. This quotient is multiplied by 100 if given in percent. The numbers given in parentheses were interpolated from Page and others (1975) for use in preparing the maps.

STEP 4: WEIGHTING THE FAULT INTENSITY MAPS

Expected damage per event can be related to total expected damage by dividing the percent damage in Table 8 by the recurrence intervals of Table 7 and discounting these amounts to their present values. If a discount rate of 10% is used, and if the term over which the costs are discounted is assumed to be forever, the present cost can be estimated by dividing the amounts calculated above by 0.10. These costs are then substituted for the intensity values in the fault intensity maps using BASIS programs.

STEP 5: MAPPING TOTAL EXPECTED COST

The costs assigned in step 4 can be summed for each area to produce a total ground shaking cost risk map for wood frame buildings and a second map for other types of buildings. These two maps were produced for each set of recurrence intervals, producing Plates 2a & b and 3a & b.

SUMMARY OF SIGNIFICANT FACTORS

Information on the following major factors are needed to produce the map of maximum expected ground shaking intensity. Changes in information used to represent any factor will change the way the final map appears.

1. Geologic materials with similar earthquake intensity characteristics.
2. Those faults on which ground shaking can originate.
3. A fault length/magnitude relationship.
4. A material/intensity/distance relationship.
5. A magnitude/maximum intensity relationship.

All of the above factors, as well as those listed below, are necessary to produce the maps of total expected cost due to ground shaking.

1. Recurrence intervals for each fault.
2. Intensity/damage relationships.
3. A discount rate.

Because of the large number of factors involved, the only cost differences among areas thought to be significant enough to map are those larger than one percent of the value of the buildings for both wood frame and other buildings. Therefore, the damage categories used on the risk maps are in one percent increments.

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This report was prepared for wide distribution in order to generate review and comment. It may require revision as new data become available.

Credits: Jeannie Perkins - Project Coordinator
Don Olmstead - Earthquake Program Director

Plate 3b

SAMPLE CUMULATIVE ECONOMIC RISK MAP FOR EARTHQUAKE DAMAGE

OTHER SMALL BUILDINGS



Assumed Earthquake Recurrence Intervals For Major Active Faults (years)

San Andreas	100
San Gregorio	1000
Hayward	100
Southern Hayward	1000
Healdsburg-Rogers Creek	100
NE of Alexander	1000
Pleasanton	1000
Calaveras	100
Concord-Green Valley	100
Antioch	100
Silver Creek	1000

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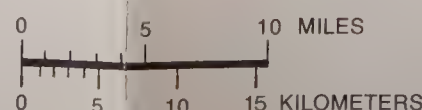


Plate 2b

SAMPLE CUMULATIVE ECONOMIC RISK MAP FOR EARTHQUAKE DAMAGE

OTHER SMALL BUILDINGS



Assumed Earthquake Recurrence Intervals For Major Active Faults (years)

San Andreas	100
San Gregorio	100
Hayward	100
Southern Hayward	100
Healdsburg-Rogers Creek	100
NE of Alexander	100
Pleasanton	100
Calaveras	100
Concord-Green Valley	100
Antioch	100
Silver Creek	100

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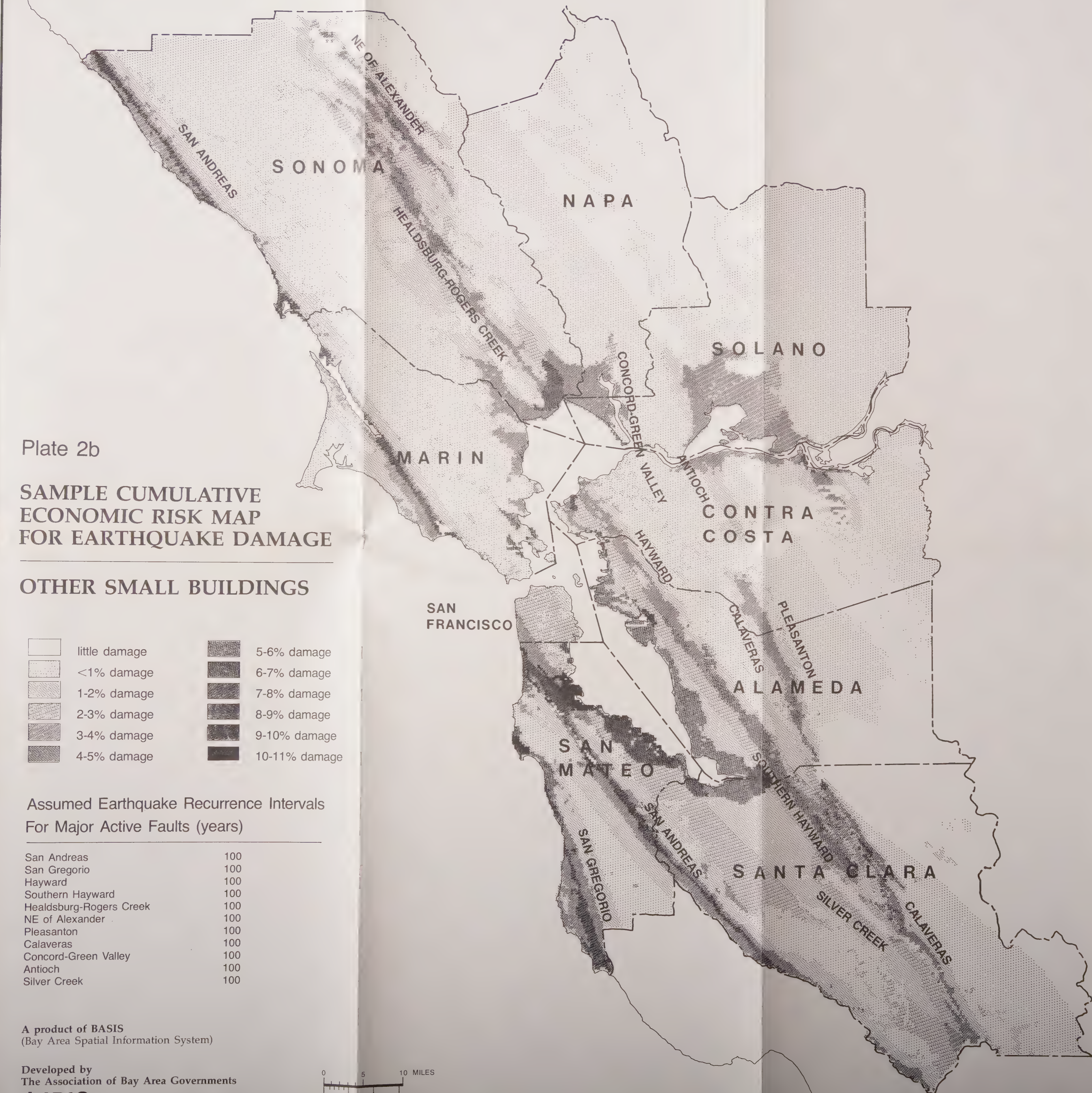
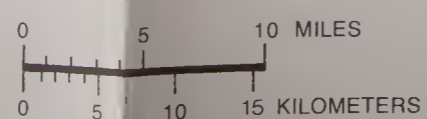


Plate 3a

SAMPLE CUMULATIVE ECONOMIC RISK MAP FOR EARTHQUAKE DAMAGE

SMALL WOOD-FRAME BUILDINGS

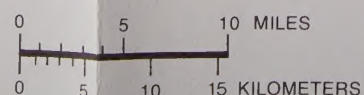
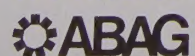


Assumed Earthquake Recurrence Intervals For Major Active Faults (years)

San Andreas	100
San Gregorio	1000
Hayward	100
Southern Hayward	1000
Healdsburg-Rogers Creek	100
NE of Alexander	1000
Pleasanton	1000
Calaveras	100
Concord-Green Valley	100
Antioch	100
Silver Creek	1000

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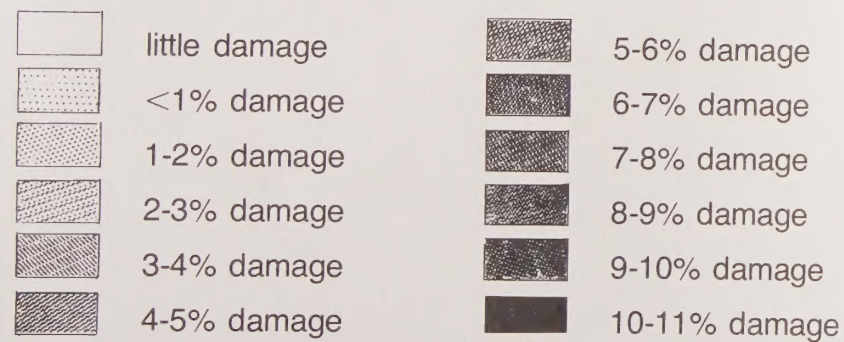


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Plate 2a

SAMPLE CUMULATIVE ECONOMIC RISK MAP FOR EARTHQUAKE DAMAGE

SMALL WOOD-FRAME BUILDINGS



Assumed Earthquake Recurrence Intervals For Major Active Faults (years)

San Andreas	100
San Gregorio	100
Hayward	100
Southern Hayward	100
Healdsburg-Rogers Creek	100
NE of Alexander	100
Pleasanton	100
Calaveras	100
Concord-Green Valley	100
Antioch	100
Silver Creek	100

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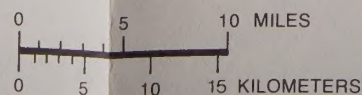
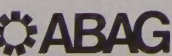
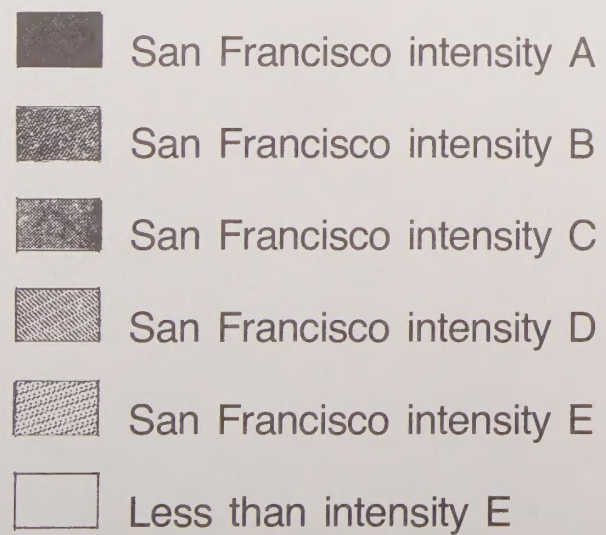


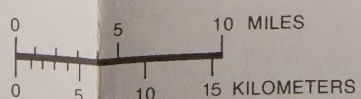
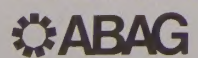
Plate 1

**MAXIMUM
EARTHQUAKE INTENSITY
FOR THE
SAN FRANCISCO BAY AREA**



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Developed by
The Association of Bay Area Governments



February 1978

SAMPLE CUMULATIVE
ECONOMIC RISK MAP

Plate 2a

Wallace,
fault i
2890.

Wood, H.
in The
Earthqu
Publica

